Montronix, Inc. (a division of Growth Finance)

Process Monitoring to Improve Machine Tool Performance

Machine tools are used to cut and shape a variety of high-quality metal components and are used extensively by major manufacturers, such as those in the automotive, aerospace, and heavy industrial sectors. Machine tools used in the automotive industry include lathes, mills, drills, and other kinds of industrial capital equipment used to fabricate components such as engine blocks and axles. In the 1990s, manufacturers were facing high costs due to downtime, rework, or scrap. Montronix, Inc. applied for and was awarded funding through the Advanced Technology Program's (ATP) focused program, "Motor Vehicle Manufacturing Technology," to improve the performance of machine tools. Montronix's proposal emphasized process monitoring to seek improvements, rather than simple tool-condition monitoring to measure wear. Montronix was a small firm without the resources to fund intensive research on its own. The University of Illinois at Urbana-Champaign (UIUC), a subcontractor, played a key role in the research.

During this project, which began in September 1995, the team performed research to develop agile systems to monitor and diagnose machine tool processes. The systems would consist of customized sensors, software to interpret the data, and Windows-based screens to display the results. Montronix and UIUC intended to transform the ability of a highly experienced machinist who could "sense" a problem into a network of sensors and computer diagnostics to analyze the same problem visually with graphical feedback displayed on a computer monitor. The research was intended to last two years (later extended to 33 months) and needed the collaborative support provided by ATP.

During the ATP-funded project, Montronix produced a prototype Machining Diagnostic system and introduced it at trade shows in 1997, while the project was ongoing. Montronix and UIUC shared the technology widely through extensive professional publications and presentations. After the project concluded, Montronix expanded by acquiring a competitor and had nine locations worldwide. They further developed and commercialized the diagnostic process. In 2001, Montronix encountered financial difficulties and was sold to Growth Finance. The company still sells systems that monitor quality and consistency, which are based on the technology developed in this ATP-funded project.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
* *

Research and data for Status Report 95-02-0020 were collected during June - July 2003.

Growth of the Tool-Condition-Monitoring Industry

A tool-condition-monitoring system measures the operation of a machine tool so that any deviation from nominal operating conditions can be identified and appropriate correction procedures can be instituted. This capability enables the production of precision, quality, and consistent parts. The first tool-condition monitoring began in the aerospace industry in the late 1970s. The sensor on this early system measured spindle deflection and when it detected a safety problem, it shut the machine down to avoid tool breakage. It relied on human intervention to recognize small problems, such as vibration and noise. Most tool-condition-monitoring systems had been installed in permanent, dedicated, continuous production systems and consisted of permanent, embedded sensor systems. The manufacturer's goal was primarily to monitor tool wear and breakage to protect the valuable machine tools. Manufacturers who used such systems have documented savings of three to five percent of manufacturing costs. The problems inherent with this method were that it was inflexible and that it focused on the machine tool, not on the product or on improving the process. This approach was adequate for long-term, large-volume production runs, but did not fit the needs of the evolving automotive industry.

In the mid-1990s, the automotive industry was trying to meet consumer demands for higher performance vehicles and more variety in the models available. The industry sought to meet these demands by trying to produce fewer identical parts with shorter machining runs; by using more flexible, general-purpose equipment; and by making frequent changeovers to new variations of parts. A primary cost of manufacturing is in setting up a production run, so the per-unit set-up costs are significantly lower if large volumes of identical components can be made. In order to cost-effectively produce a greater variety of smaller runs, manufacturers had to cut production costs by making more efficient use of labor (setting up and running these small production runs) and by producing less waste material (making precision parts right the first time and every time). Auto manufacturers needed to establish break-even points for models at unit-production volumes that were lower than they had achieved in the past.

Precise Machining Adds Value

Automotive components must be manufactured with high precision, and tolerances must be measured in the thousandths of an inch. Surfaces must be precisely parallel or perpendicular, perfectly round or square, depending on the specifications. With thousands of parts on a single car, any mismeasurements can result in alignment problems; or worse, the components simply will not fit. Parts that do not meet specifications have to be scrapped.

Machining a metal workpiece requires that it be placed securely and precisely on the base and that consistently sharp tools be used to cut it in order to avoid rough edges, crooked cuts, or damage to the part or the tool. An example of a component that posed challenges for auto manufacturers is the stamping die for producing body panels. A single stamping die is a high-value machined component. Dies are used on the assembly line to stamp sheet metal into automotive body panels. Because the quality of the panel is directly dependent on the dimensional precision of the dies that form it, dies must be machined very precisely. To achieve a desired final shape, the sheet metal is successively stamped (i.e., sandwiched between an upper and lower die) by a series of dies, each of which adds increasing geometric detail.

Stamping dies may be valued at hundreds of thousands of dollars. The primary cost factors in making the die are in the time and effort to test and retest the die before it is used in the manufacturing process. First-quality auto body panels depend on precise machining of the dies. Detecting defects such as voids, holes, or gaps in the metal must be done early in the process. An error introduced late in the process destroys the die and all the machine time and labor invested in it. Moreover, meeting production deadlines is critical to a successful model release. Any delay in producing a die could delay the release of a new automobile model, thereby increasing the cost of release (costs for releasing one new model, for example, are between $1.5 and $4 billion).

The industry strives for flexibility, speed, precision, low cost, and quality. Oftentimes, these are conflicting goals. Machine tools need to be flexible and need to be able to perform a variety of tasks. Components must be produced reliably, precisely, and quickly, with little or no waste and downtime (which results in lost material and labor). Manufacturers want to identify and remove defective parts as early in the process as possible and want to avoid introducing new errors. Machine-tool-monitoring systems can perform a vital diagnostic role in these tasks.

Montronix Seeks to Monitor Tools Intelligently

Montronix was an innovative provider of tool and process-monitoring systems for metal-cutting machines. The company believed that it could develop products to meet the challenges of reducing downtime, rework, and scrap. The University of Illinois at Urbana-Champaign (UIUC) Machine-Tool Agile Manufacturing Research Institute specializes in developing innovative machine-tool concepts and systems to stimulate national manufacturing competitiveness. Montronix and UIUC observed the weaknesses in the existing dedicated monitoring systems, which could not measure status frequently enough and thus allowed too much waste material. The existing solution was to stop production frequently to measure completed parts (this reduced production volume) and thereby assure that measurements were within specifications. Montronix and UIUC identified a concept to link sensors, hardware, proprietary software, and Windows-based personal computers (PCs). The sensors would detect vibration, force, speed, and temperature. The customized computer screens would visually depict the machining process, that is, the nominal (perfect) operations and the various problems that might arise.

This next-generation tool/process-monitoring system would be extremely precise in detecting changes in the monitored data coming from the sensors. These data changes would indicate process changes that can occur from variables in the manufacturing process, such as raw stock material variations (e.g., blemishes and imperfections in the metal), speed and feed rate changes, tool wear or breakage, and improper programming (e.g., the engineer set a measurement for 0.1 inches instead of 0.001 inches). The intent was to monitor the process in order to track performance and seek improvements, as well as to monitor the condition of the tools and notify the operator when the machine tool has a problem. Montronix and UIUC's plan consisted of the following:

- Use process modeling to interpret a process signal that contains one or more process faults
- Develop a fault diagnosis framework to identify underlying causes, based on the comparison with process-model-generated data
- Relate performance measures with ideal sensor or model information in a flexible diagnostic system
- Collect process data at high speeds and develop meaningful diagnostic parameters
- Present these data in graphs on a Windows-based screen
- Transform these data into solutions and improvements
- Perform comparative tooling studies

The new system would also need to be more versatile, diagnostic, portable, and sensitive; moreover, it would need to be easily and unintrusively introduced into new or existing machine tools operating on the production floor. A system with these qualities would allow real-time adjustments and would keep measurements within specifications.

Field Tests Are Performed at an Automotive Plant

In order to test their project results, in March 1997, the Montronix/UIUC team conducted field tests. They used their prototype Machining Diagnostic (MD) system, which they had developed during this project, to detect process variations at a particular machining station in an automotive plant. The station conducted face-milling operations on a cylinder block line. The test involved three milling cutters with varying diameters. The plant had experienced downtime at this station due to several process variations, and the manufacturer had requested that Montronix investigate the problem.

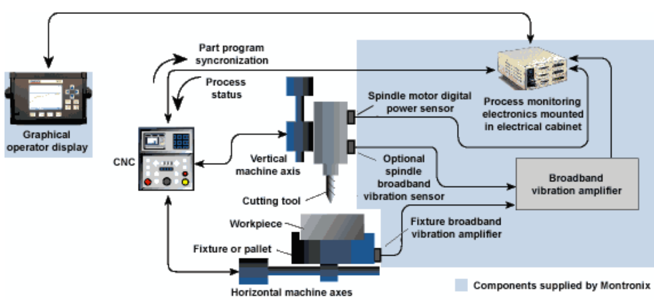
The MD system was a computer-based diagnostic tool for rotating tool-machining processes that played a critical role in manufacturing many engine, transmission, and brake parts (see illustration below). The system used force and vibration sensors to collect data. It also used a digital signal processor (DSP) design that could sample and analyze sensor signals 5 to 10 times faster than a typical tool-monitoring system. The MD system used proprietary software to model the process and to diagnose faults, so the operator could rapidly collect, visualize, and analyze sensor data from machining processes. The MD system could analyze gears and other rotating assemblies. Utilizing easily attached retrofit sensors that were synchronized with spindle rotation and sophisticated DSP techniques applied in real-time, the MD system could be used to accomplish the following tasks:

- Detect and isolate process faults such as run-out (measurements outside of specifications), throw, tilt, and misalignment
- Detect tool problems such as regrind errors, insert chipping, and breakage

- Assess the state of the machining process, rate of tool wear, and risk of tool breakage

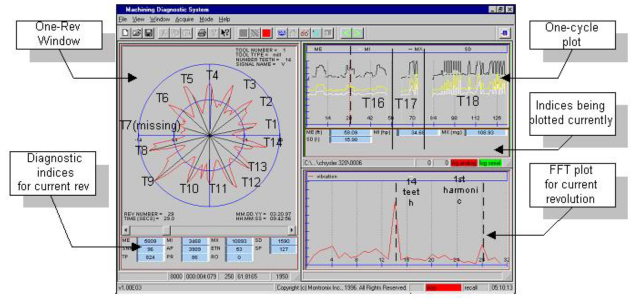
- Quantify vibration and noise in rotating assemblies

The Montronix MD system is a portable analysis tool for benchmarking and fault diagnosis in machining operations involving rotating tools. It includes a laptop computer with visual display and proprietary software to interpret data from the sensors.



In the diagram, note that sensors adhere to and monitor the machine tool's base, cutting tool, and motor. The data feeds Montronix's software, which continuously updates the Windows-based PC screen. The operator uses this feedback to update parameters on the machine tool itself through the computer-numerically controlled system.

The system extracts cutting signals on per-revolution and per-tooth bases, providing detailed diagnostic information (see illustration below). In the field tests, the system successfully detected insert breakage on one cutter and detected run-out and high vibration levels on another cutter much faster than was possible with a non-Montronix signal level. The team later conducted successful trials at three additional manufacturing locations for gear knock testing, turning of Teflon pump seals, and machining center testing.



This sample MD system software window layout displays the detailed information that would appear on the operator's screen. The example shows a missing tooth, number T7 of 14.

Project Team Meets All Milestones

At the end of the project in 1998, the team had met all its major milestones and technical goals:

- The team completed and tested the MD system. The system could sample data from retrofit sensors synchronously with tool rotation, process the data and extract diagnostic indices, and plot/store the data and indices in a Windows 95 software program. This system was introduced at trade shows in Detroit and in Hanover, Germany in September 1997.

- The UIUC achieved significant results in the mechanistic modeling and fault diagnosis areas. They enhanced models for end milling, face milling, and drilling to include geometry faults and tool breakage and chipping effects. The models proved useful in identifying and estimating multiple fault conditions and retrofit sensor data.

- The team achieved successful results for many of the high-risk tasks. These included developing a prototype MD system using synchronized sampling, retrofit sensors to characterize fault conditions, mechanistic models to predict fault behavior, and model-based fault diagnosis techniques.

By the end of the second year of the project, Montronix was promoting, testing, marketing, and selling the first release of the system, both as a portable diagnostic tool and as a dedicated monitoring module. The team published several articles and presented numerous lectures at conferences to share their knowledge within the manufacturing sector.

Tool Monitoring Enables Automation and Quick Response to Errors

The ATP-funded project continues to have an impact on machine-tool-process monitoring. The Montronix MD system uses menu-driven set-up routines and graphical feedback displays, which simplifies setting up, modifying, and monitoring the machine-tool process. The operator can learn to use the system in a matter of hours. Online tool monitoring enables greater automation, quicker response times to errors, and faster, more streamlined machining.

According to Professor Richard DeVor of UIUC, "This project allowed the team to develop a better understanding of machining processes to identify faults in data. We developed mathematical modeling, which carried on considerably past this project, benefiting the entire machine tool industry. New knowledge was developed, showcased in meetings, and momentum gained."

A key accomplishment of this project was providing free Internet-based simulated machine-tool modeling (http://mtamri.me.uiuc.edu/testbeds/testbed.intro.html). The web-based simulation is still in use by government, academic, and industry researchers. The web-based end-milling project, which includes fault modeling and diagnosis, has been execute online more than 50,000 times by government agencies, universities, and industries.

The team developed code, software, and algorithms (for the first time on a Windows platform). In addition, the team made advances in speed, user friendliness, and the ability to apply improvements from one component manufacturing process to another. The monitoring system developed in this project evolved into a standard Montronix product line called Spectra.

Finally, research into this area is ongoing. After the conclusion of this project, Montronix received internal funding and government grants for additional research. UIUC has continued tool-process-monitoring research and development work. They publish and provide ongoing cutting-edge research for individual manufacturers, which pay $50,000 annually for membership in UIUC's manufacturing consortium.

Montronix Monitoring Continues to Impact Manufacturing Efficiency

One of the significant aspects of this project was developing user-friendly Windows-based proprietary diagnostic software to monitor and view the process and diagnostics. Montronix later conducted additional research and further developed the MD system technology, which led to the production of several process controllers in the Spectra series, released in the fall of 2002. This next-generation diagnostic system includes a miniature monitoring system that uses micro-electronic-mechanical-systems technology. The company has installed more than 5,000 diagnostic systems worldwide. These systems are benefiting consumers by increasing efficiency and reducing manufacturing costs.

The web-based end-milling project has been executed online more than 50,000 times by govermnent agencies, universities, and industries.

In a factory setting, a complex, multistage machine tool may require several Montronix systems. For example, one manufacturer uses approximately 400 Montronix diagnostic systems to monitor the process and the machine tools for horsepower, force, and vibration. The engineers report that the systems are most effective in detecting deviations in highly repeatable machining processes.

Another manufacturer uses eight Montronix systems. One machine tool has a large right-angle head whose gears need to be replaced approximately every three months, at a cost of $12,500 per head. An installed Montronix system consistently recognizes the increased vibration very early, which means that the head can be rebuilt for only $2,500. In addition, all waste parts have been eliminated, saving the material and labor from rework. This factory plans to install six more Montronix systems as soon as it can stop production long enough to do the initial set-up.

Market Conditions Affect MD System Sales

Although market potential seemed significant and the project achieved technical success, sales were disappointing due to factors beyond Montronix's control. Montronix believed that after the project, the enabling technologies would be developed to the point where the company, in partnership with one or more automotive "Big Three" companies, could expand. However, they were unable to finalize the desired partnership, so they acquired other small companies and expanded into nine global locations.

Moreover, use of monitoring tools among manufacturers has been limited. For example, while there are approximately 3 million machine tools on the market, the current penetration for monitoring tools is only about 5 percent. Of these 150,000 monitoring tools, Montronix's share is approximately 5,000 monitoring systems worldwide. Montronix competitors provide only low-end standard monitoring systems, which lack the fault diagnostics elements. A few major manufacturers are using the Montronix systems for individual manufacturing processes. Usage is not widespread, even though the potential to achieve competitive advantage through process monitoring is tremendous.

Unfortunately, the anticipated growth in monitoring systems sales has not occurred. Major changes have taken place in the automotive industry, and sales have failed to meet expectations. For example, since 1998, auto manufacturers have been forming a variety of mergers, acquisitions, and alliances, blurring national boundaries and reducing the number of manufacturers. Off-shore production plants have lower labor costs, which reduces the impact of process monitoring labor savings. The performance of U.S.-based companies now reflects the global economy. Reducing overall costs has become a higher priority than improving U.S. manufacturing efficiency. Manufacturers are cutting costs by reducing the number of component parts, the number of dies for stamping sheet metal, and labor; they are also outsourcing parts production and receiving parts on an as-needed basis. U.S. unions complain that manufacturers are moving operations to low-wage countries such as Mexico and China. This trend is expected to continue; therefore, the manufacturing plants that could benefit from Montronix systems are being transferred outside the United States.

Following the recession in 2000 to 2001, the U.S. manufacturing recovery has been slow; for example, 2.6 million manufacturing jobs have been lost, representing a 15-percent employment drop in this sector. Montronix was not able to survive the economic downturn. In 2001, the company was purchased by Growth Finance, a Swiss-based company. In 2003, it had 40 employees, up from 24 at the project's start in 1995, but down from a peak of 80 in 1999. As a part of Growth Finance, Montronix now continues to sell the Spectra-series process controllers, built on MD system technology.

Conclusion

In this ATP-funded project, Montronix and the University of Illinois at Urbana-Champaign pioneered diagnostics for machine-tool monitoring and met all their major technical milestones. The project team focused on using real-time data to improve the manufacturing process as well as the components produced. Montronix Machining Diagnostic systems monitor the state of the workpiece and the rate of wear on the machine tool itself. The system compares the performance of two or more similar processes in order to consistently seek manufacturing process improvements. The technology developed during this ATP-funded project incorporated advances in PC computing power and speed, user-friendly Windows-based software, and precision in sensor measurements in machine-tool monitoring.

An installed Montronix system consistently recognizes the increased vibration (in a right-angle head) very early, which means that the head can be rebuilt for $2,500. In addition, all waste parts have been eliminated. This factory plans to install six more Montronix systems.

The team published many articles and gave numerous presentations about the process-monitoring techniques. They also developed a free, Internet-based simulation that is still available to government agencies, industries, and universities. In 2001, Montronix experienced financial difficulties and was sold to Growth Finance. Although the technology was a success and led to the development of Montronix's Spectra series, it is undersold at this time due to major changes in the automotive industry. The future of the business is uncertain.

PROJECT HIGHLIGHTS
Montronix, Inc. (a division of Growth Finance)

Project Title: Process Monitoring to Improve Machine Tool Performance (Machine Tool Process Monitoring Diagnostic System)

Project: To develop a diagnostic system that can monitor the vital signs of machining operations in real time to provide a trouble-shooting aid for process engineers who are increasingly challenged to efficiently machine smaller volumes of a wider variety of parts.

Duration: 9/1/1995 - 6/14/1998
ATP Number: 95-02-0020

Funding (in thousands):

ATP Final Cost	$ 1,225	81%
Participant Final Cost	295	19%
Total	$ 1,520	

Accomplishments: The pioneering research and development in this project led primarily to advancements in sensors to record the state of the workpiece, the cutting tool, and the machine tool motor, as well as the development of proprietary software on a Windows-based platform. Montronix monitoring system users can adjust machine tools on the fly to maintain precision in their components. This shortens set-up and testing time, reducing wasted labor and material. As part of this work, the team developed simulations of end-milling projects that are still provided for free on the Internet for use by engineers and scientists.

The initial Montronix Machining Diagnostic (MD) system laid the technological foundation for five Montronix products (as of 2003):

- Spectra PC for open architecture controls
- Spectra Gold for flexible, multistation tool and process control
- Spectra Silver for flexible tool and process control for single machine or process applications
- Spectra Blue for single machine or process crash detection
- Spectra Pulse for complete monitoring systems in a miniature package

Commercialization Status: Based on the MD system developed in this project, Montronix developed another generation of the technology, the Spectra series, which it still markets. More than 5,000 Montronix systems are being used by manufacturers to improve the efficiency of their machine tools. One product developed during the ATP-funded project, the free, web-based machine tool modeling simulation for end milling, is still in use. It has been executed more than 50,000 times for government, research, and industrial use. Montronix expects to continue marketing Montronix diagnostic systems, but the future depends on the manufacturing industry's health, especially that of the automotive industry.

Outlook: The outlook for Montronix process-monitoring tools is uncertain. The company made dramatic advances in speed, user friendliness, and process enhancement; however, the technology enabling these efficiency and precision improvements is undersold. It is difficult to measure the impact of Montronix diagnostic systems, because manufacturers are unwilling to divulge statistics on their efficiency improvements.

Composite Performance Score: * *

Focused Program: Motor Vehicle Manufacturing Technology, 1995

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PROJECT HIGHLIGHTS
Montronix, Inc. (a division of Growth Finance)

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